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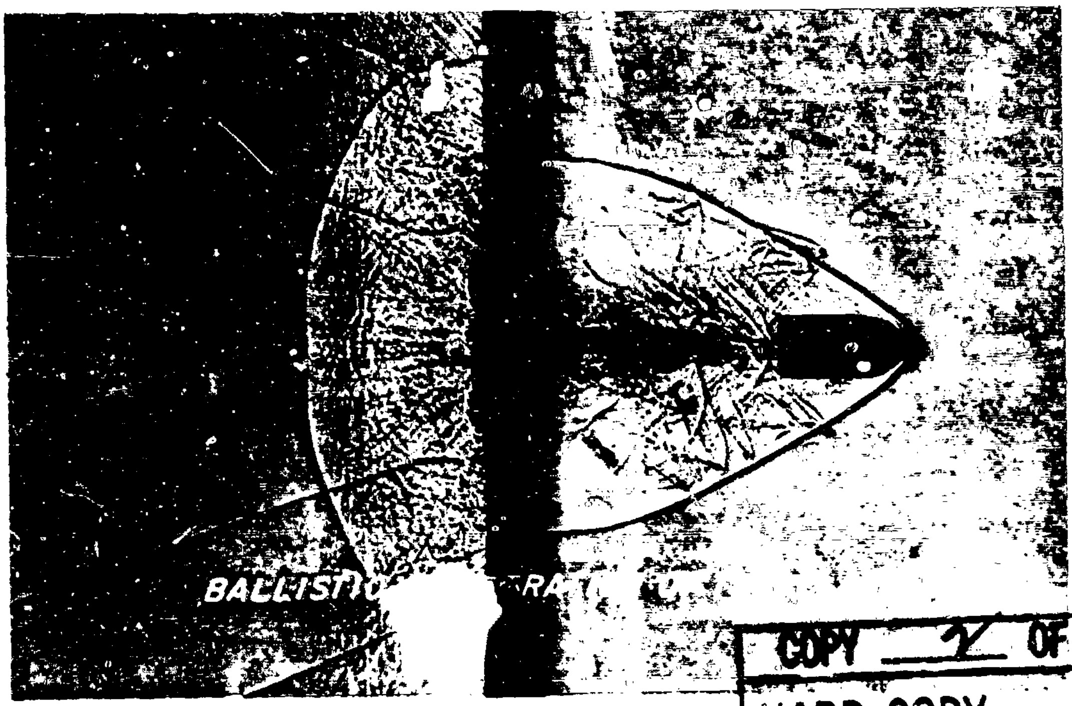
## *Monograph Series*

# BALLISTIC CONCEPTS EMPLOYED IN TESTING LIGHTWEIGHT ARMOR





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# BALLISTIC CONCEPTS EMPLOYED IN TESTING LIGHTWEIGHT ARMOR

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Since the turn of the century, ballistic evaluation of lightweight fragment-resisting armor by simulation of service conditions of attack has been a continuously changing problem for all services because of new specialized weapons and materials which are introduced constantly in modern warfare.

During World War I, fragment-resisting armor (first modern helmet[1]) was tested with caliber .45 ball ammunition since it was the principal type of service ammunition which was defeated by the helmet. Consequently, this ammunition was adapted for evaluating the ballistic performance of fragment-resisting armor. As the years passed on, this test was questioned by many research laboratories and testing stations. The mechanism of penetration by the very deformable mushrooming pistol ball projectile is markedly different from that of steel or cast iron shell fragments which have become a major source of battlefield casualties. Armor materials that offer superior resistance to caliber .45 ball ammunition may provide reduced resistance to HE Shell fragments. It has also been found, to the great confusion of testing facilities, that the caliber .45 ball, M1811, ammunition is far from being sufficiently uniform in production manufacture and ballistic performance to be satisfactory for use in ballistic testing and evaluation; although the lack of uniformity did not affect its suitability for combat use.

To conserve critical materials during World War II, these projectiles varied in content from very soft unalloyed lead to considerably harder alloys containing tin or antimony. Caliber .45 ball ammunition filled with the harder alloyed lead had considerably greater penetration potential. Early production lots of ball ammunition were made with gilding metal jackets, while subsequently, as a means of conservation of copper, they were jacketed with copper-clad steel. This latter ammunition again had superior penetration performance because of the harder steel jackets. All of the above types of caliber .45 ball ammunition have been used at one time or another to evaluate the ballistic performance of helmets and fragment-resistant armor, and the ballistic results were confusing and conflicting because of the variations in the properties of ball ammunition. The caliber .45 ball copper-clad steel-jacketed projectile perforated the American World War II helmet at velocities as low as approximately 600 feet per second; whereas the same helmet resisted the attack of copper-jacketed, soft-lead-filled bullets at their service velocity of approximately 850 feet per second.

The caliber .45 ball ammunition has been discarded by the Ordnance Corps for use in evaluating armor materials because it does not represent the type of battlefield missiles (shell fragments and armor piercing projectiles) encountered in modern warfare. Its penetration of armor materials

is entirely different from that of shell fragments, a condition which provides results which are meaningless or even misleading.

An empirical approach was then taken by the Ordnance Corps in assessing the ballistic resistance characteristics of fragment-resistant armor. A test was conducted by placing test samples in a circular arrangement[2] (varying the radius from the point of detonation) and detonating HE Shell placed at the center of the circle. These tests were evaluated on a statistical basis in an effort to obtain reliable and reproducible results. The ballistic characteristics of the armor were expressed in a number of ways, such as (a) the number of perforations per unit area of armor surfaces; (b) the percent of impacting fragments which perforate the armor; or (c) the residual energies of perforating fragments which may be evaluated by means of a series of witness plates placed behind the armor. The number of witness plates one behind the other, which could be perforated provided an index of the residual energy possessed by the fragments. A large area was needed to conduct these tests, which were costly since many samples were placed around the shell in order to obtain statistical data. This type of test is still employed occasionally to obtain statistical data on fragment penetration.

A similar test, which was employed to evaluate personnel armor, was set up by the Ordnance Corps[3] during World War II. Armor materials were tested by a controlled fragmentation side-spray test. A 20MM shell, HEI MK-I, was statically detonated inside a rectangular or triangular box test set-up. Three or four recovery boxes 12" x 12" were used to recover the fragments that perforated the armor samples being tested. (See Figure 1 for a triangular test arrangement.) A total of twenty 2024-T3 aluminum alloy sheets, 0.020" thick, were spaced at one-inch intervals behind the armor samples. The 20MM shell was suspended nose-up in the center of the square or triangle, and the shell was statically detonated. The HE fragments which perforated the test panels were recovered and identified as to the box and zone number in which the fragments came to rest. The firing process was repeated until the desired number of samples had been tested. The recovered fragments were weighed and the weighed totals computed according to set standards. Some of the disadvantages of these tests were: (1) they were cumbersome; (2) they required a large quantity of test panels; (3) they were expensive to perform; (4) they yielded data difficult to reduce to simple expressions of ballistic merit such as a merit factor or a ballistic limit.

A controlled forward spray type of test was set up by the Naval Proving Ground, Dahlgren, Virginia,[4] for rating lightweight armor materials. In this test a 20MM HEI shell is fired with a striking velocity of 2700 + 50 feet per second at a 0.125" cold-rolled mild steel plate (hardness of RB50 ± 10), which is called a triggering plate (See Figure 2) since it detonates the HE Shell. The armor sample which is being tested is mounted normal to the line of fire and three feet beyo d the triggering plate. The triggering plate is positioned so that the projected line of fire passes through the center of the triggering plate and through the center of the test sample. The result of any round whose center of impact on the mild steel triggering plate is greater than 5" from the center of the

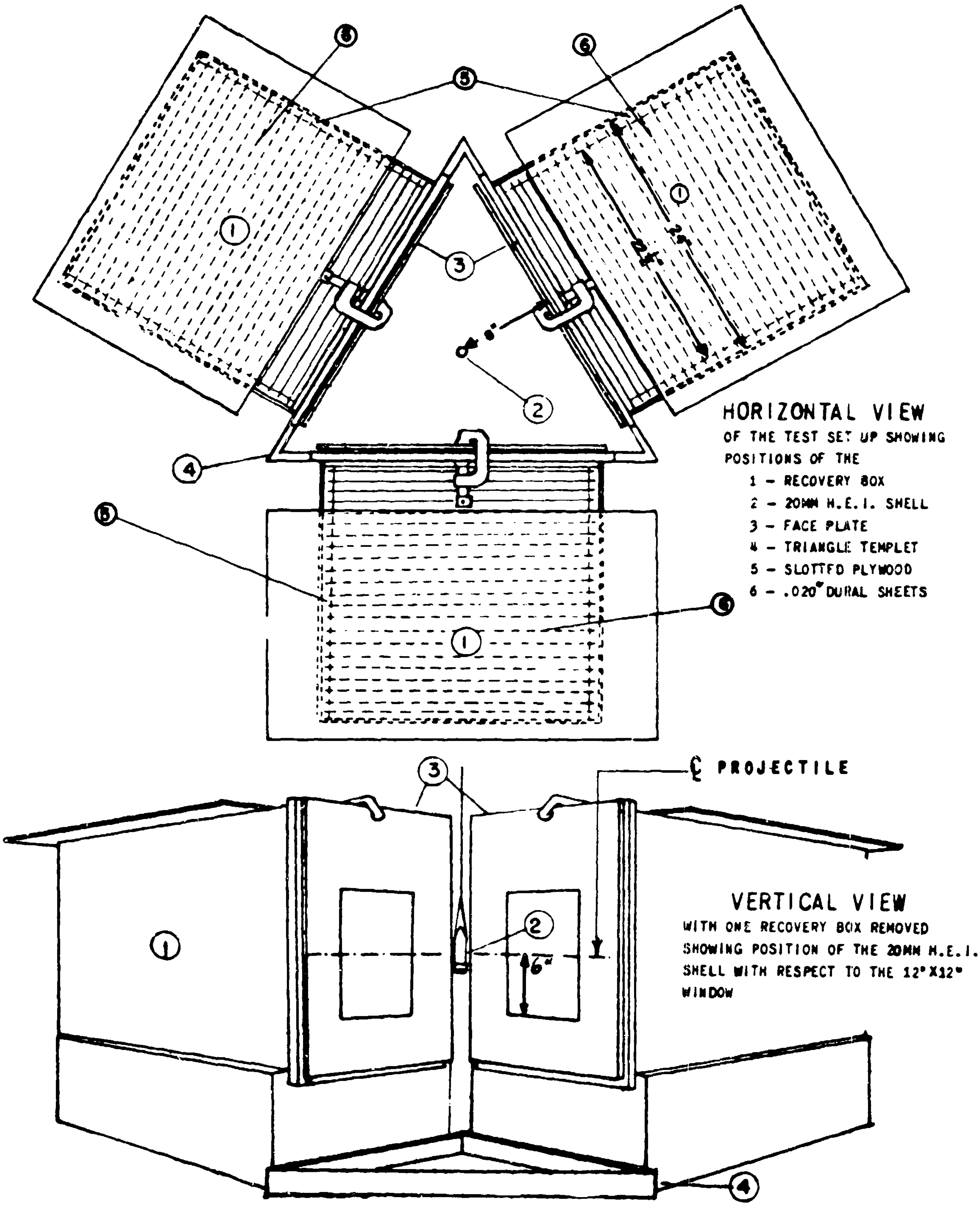


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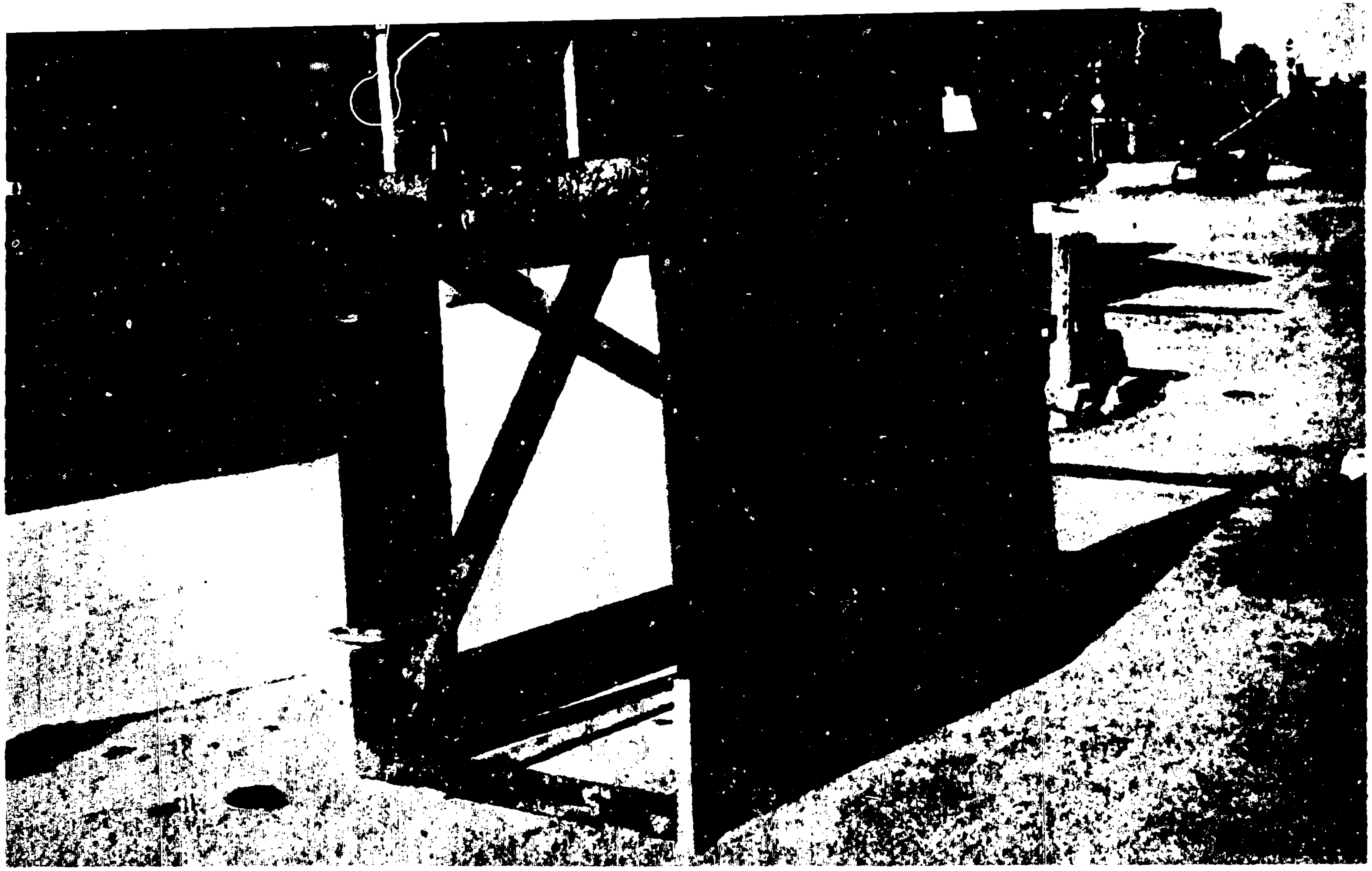
FIGURE 1



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NPG PHOTO NO. 28630 – MOUNTING OF ARMOR FRAGMENT RESISTANT PANELS (NON-METALLIC) ( APPROX. WT. 1.2 LBS. PER SQ. FT.) FOR TEST WITH FORWARD FRAGMENT SPRAY FROM 20MM HIGH EXPLOSIVE PROJECTILES. 5 DEC 1944 FRONT VIEW Wtn. 639-16,782

detonating plate is discarded. The firing process is repeated until a statistical number of samples has been tested. A statistical analysis is made on the number of complete penetrations obtained for given areal densities of armor. The material which has the least number of penetrations for a given areal density is rated as the best from a protection viewpoint.

Multiple cube testing was investigated[5] after World War II. In this test approximately 31 cubes of uniform weight were fired in a phenolic plastic sabot. The 3/16", 1/4", 5/16", 3/8", and 1/2" cubes employed weighed 13, 31, 61, 104 and 245 grains respectively, and were hardened to a hardness of Rockwell "C" 23 to 28. The plastic sabot which contained the number of cubes of uniform size was fired from a rifled 57MM M1 gun, and the velocity of the forward cube was measured and taken to be representative of the velocities of all cubes. The mean velocity and percentage of complete penetrations were determined for each round fired from which a V50 limit velocity* and a limit penetration coefficient** were computed and used as a basis of comparing material. Disadvantages of this type of ballistic test were:

a. There were variations in results since the measured velocity employed was that of the fastest cube, whereas a velocity distribution actually existed.

b. The velocity spread between the highest measured velocity and the mean velocity varied considerably, especially for the smaller size cubes.

c. The non-uniform dispersion of cubes from round-to-round added to the confusion and caused difficulty in interpretation of results.

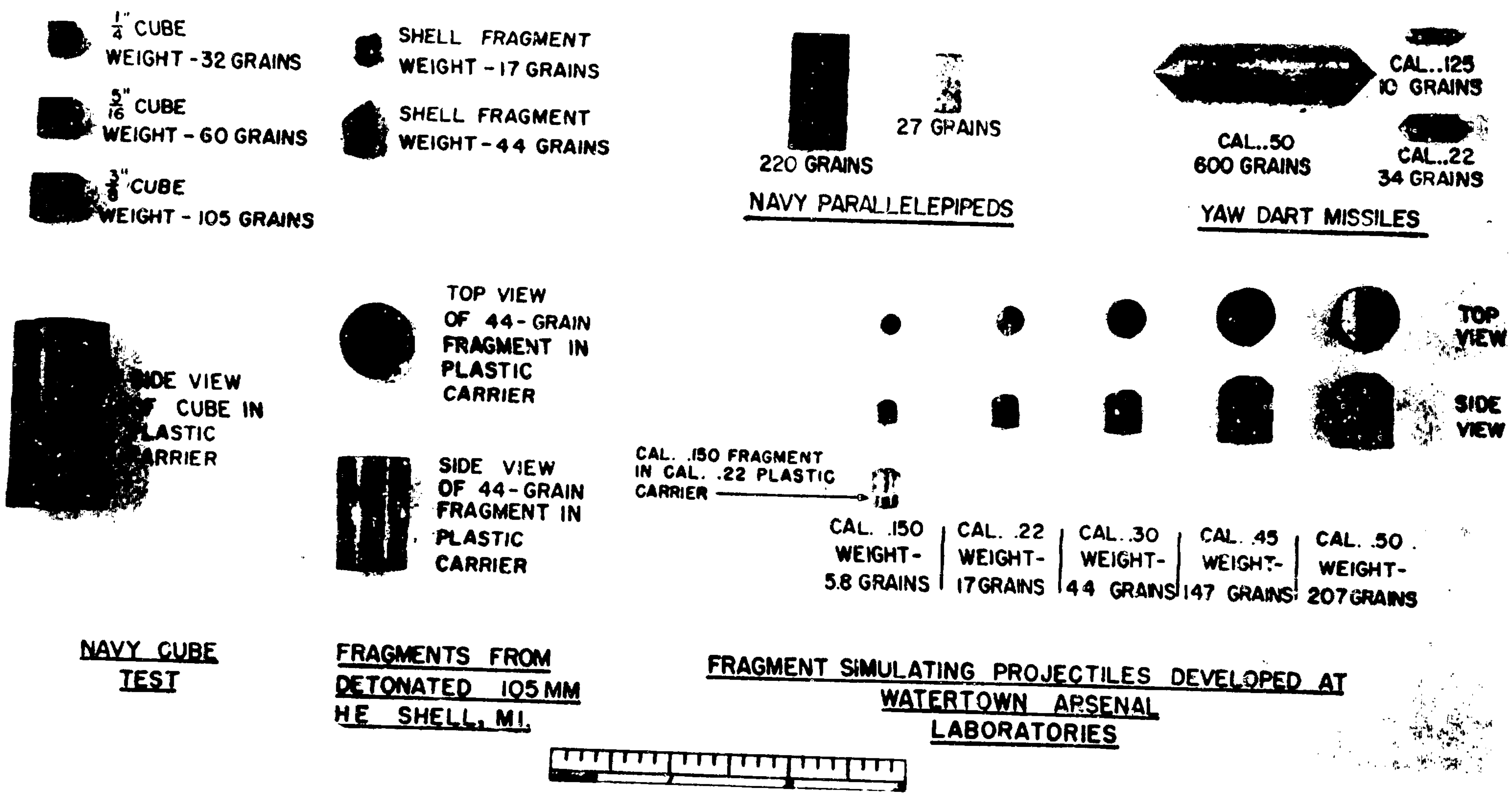
The multiple cube test was abandoned in favor of the single cube test because of greater simplicity and reliability. In a single cube test, steel cubes of known sizes were sheared from cold roll square bar stock having a hardness of approximately 28 Rockwell "C". The cubes were individually mounted in plastic carriers (See Figure 3) and fired from rifled guns. The plastic carrier provided for rotation and gas seal for the missile. The cube broke out of the carrier upon emerging from the muzzle of the gun and traveled down range to the target. The cube may impact the target on its edge, corner, or side. These variations increase the scatter in the ballistic evaluation because the mechanism of penetration of the cube changes from impact to impact depending upon how the cube strikes the target.

*A V50 limit velocity is an estimate of the mean velocity at which, on the average, 50% of the cubes striking the target will defeat it. A defeat is considered to have occurred when there is a through hole in the target which will allow the cube or major portion thereof to pass through.

**A limit penetration coefficient $F$ is defined as follows: $F = \frac{M \; V50}{e \; A}$

Where: $M$ = Cube mass (grains)
$e$ = Equivalent plate thickness (inches)
$A$ = Cube face cross section (inches2)
$V50$ = Limit velocity (feet per second)

# SHELL FRAGMENTS AND FRAGMENT-SIMULATING PROJECTILES USED TO EVALUATE RESISTANCE OF ARMOR MATERIALS TO PENETRATION BY SHELL FRAGMENTS

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Single and multiple sphere types of ballistic tests have been conducted by some research establishments in evaluating fragment-resistant armor. In the single sphere test the sphere is launched from a smooth-bored gun (or the sphere can be placed in a plastic cup and launched from a rifled gun). In a multiple sphere test a plastic sabot is employed to launch spheres. These tests are similar to the cube tests that were described in the preceding paragraphs. A major disadvantage of this test is that spheres do not have jagged or sharp edges. As a result they do not exhibit the same mechanism of penetration as HE Shell fragments.

Another method of assessing the performance of armor for protection against shell fragments, which was developed by Watertown Arsenal, consists of detonating a standard HE Shell, recovering the fragments, screening them into weight classes, and then selecting and firing individual shell fragments from a given weight class at an armor sample to determine a ballistic limit in the conventional fashion; i.e. firing enough fragments of a selected weight group (See Appendix A for definitions of a ballistic limit). The shell fragments are individually mounted in plastic cups (See Figure 3) in which they are held in place by sealing wax and fired from standard rifled guns. The fragment breaks out of the cup upon emergence from the gun tube and proceeds down-range to impact the armor.

Although this method represented a significant improvement over previous tests it still has several limitations. First, it is necessary to secure and detonate HE Shell, recover, screen, and weigh fragments - a not inconsiderable task. Furthermore, variations in mass and geometry of shell fragments falling within one weight class introduce sufficiently wide scatter in test results (wide zone of mixed results) to necessitate firing a moderately large number of fragments to obtain a reproducible (V50) ballistic limit. Finally, variations in the mechanical properties of shell steel are so wide that shell fragments display a broad range of deformation and fracture characteristics, thus influencing their ability to penetrate hard metallic armor materials and affecting the ballistic limit. However, against fabric or plastic armors which are relatively soft the projectile's hardness does not affect the ballistic performance significantly. This test is used to evaluate the value of other methods, such as the one described next, by assessing their ability in providing a rating consistent with that obtained with actual shell fragments.

In order to overcome the above deficiencies, but still retain the major advantages inherent in the above method, Watertown Arsenal Laboratories developed a homologous series (1.35 to 830 grains) of fragment simulating projectiles which consists essentially of cylinders having blunt, chisel-shaped noses and raised flanges at their bases to act as gas-seals and rotating bands. These missiles are hardened to Rockwell "C" 28-32. This hardness level was selected after determining that this represents the average hardness range of recovered fragments of detonated 20MM, 37MM and 105MM HE Shell of domestic manufacture. Ballistic tests of these fragment simulating projectiles demonstrated that they were stable in flight and yielded significant results. Numerous tests[7] have been conducted with both actual shell fragment and fragment simulating projectiles having the same weight, hardness and mechanical properties

to determine their comparative ballistic performance when fired at various types of fragment armor materials. The results show that the fragment simulating projectiles satisfactorily simulate the penetration performance of actual shell fragments since they rate armor in the same order of superiority. Firing with a fragment simulating projectile however, is fairly simple compared to testing with HE Shell or individually-fired shell fragments. In addition, the scatter of the resulting data is quite small thereby providing greater accuracy and reproducibility with a minimum number of rounds.

A yaw dart projectile has been developed by the Naval Research Laboratory, Washington, D. C., for testing and screening experimental lightweight armor material. The dart is a cylindrical missile with $90^{\circ}$ cones ground on each end and heat treated to a very high hardness (approximately Rockwell "C" 60-63) so that the projectile is essentially nondeforming during impact. The technique used for making controlled yaw impacts involves firing into a ballistic plate testing pendulum at close range through a blast deflector. A light upsetting plate is fastened to the rear of the blast deflector in such a position that the dart missile will graze the edge of the upsetting plate. Projectile yaw develops thereafter at a rate predictable over a range of several feet. Orientation of yaw at any point may be varied by rotating the deflecting plate. The rate at which yaw develops depends upon the dart velocity. Precise velocity control is desirable both for the purpose of closely bracketing limit velocity points and for the purpose of maintaining accurate control of yaw. Generally, the dart missile is deflected such that it will impact the armor broadside. A sufficient number of complete and partial velocities are fired so that the limit velocity may be calculated. The yaw dart missiles provide less kinetic energy per unit area than do most shell fragments and only represent an extreme condition which occurs with very few shell fragments.

Parallelpipeds, flat-end right circular cylinders[8] and hemispherical nose-type missiles have also been investigated and employed in the ballistic testing of armor. Tests have shown that each of these missiles differ somewhat in its mechanism of penetration into an armor material. These missiles have not been employed for materials acceptance testing since they do not have the attributes of simplicity, consistency and reliability desired in a test for rating armor materials. Since the mechanism of penetration of armor affects the rating of fragment-resistant armor materials, it is especially important to elaborate on this subject. When metallic armor is perforated by HE Shell fragments, there are two principle ways or mechanisms by which the perforation is effected. These may be called the "pushing-aside" or "ductile" mechanism and the "plugging" or "shearing" mechanism. In the first, the missile forces its way through the armor by displacing the material sideways, building up bulges on the front and back surfaces of the plate and laterally compressing the material in the interior of the plate. The harder the material the more resistant it is to lateral displacement. Thus, when the pushing-aside mechanism of penetration is the one that occurs, the resistance to penetration increases with increasing hardness of the armor. The plugging mechanism involves the shearing out from the metallic armor of a cylindrical disc, which is ejected ahead of the missile. There is relatively little deformation and

no lateral compression of armor when this type of penetration occurs. Harder materials tend to plug more readily and completely than softer materials, and thus above a certain hardness, the plugging mechanism of penetration is involved, and the resistance to penetration decreases. Other factors besides hardness of the armor which determine the mechanism of penetration include the following:

1. Ratio of plate thickness to size of the HE fragment; the larger the presented area of the missile at impact, the greater the tendency toward penetration by the plugging mechanism.

2. Blunt-nosed missiles tend to plug the metallic armor while sharp-nosed missiles tend to pierce and laterally displace the plate material. An important fact to keep in mind is that when plugging occurs, less energy is absorbed than when penetration is effected by the pushing-aside mechanism. Since shell fragments are blunt missiles, the penetration of armor by HE fragments generally involves plugging. Perforation of some materials such as aluminum and magnesium alloys, which are soft and overmatch (armor thickness greater than the projectile diameter) the projectile, is effected by a combination of the two mechanisms of penetration. The material is displaced sideways during the first stage of penetration and then finally plugs when the fragment approaches the rear surface of the plate.

In obliquity tests the length of face impressions upon the plate under any set of test conditions can vary from round to round. In general, in the intermediate velocity range (1800 to 3800 feet per second) complete penetrations on good quality armor are usually associated with short lengths of face impressions while partial penetrations are associated with longer lengths of face impression. At certain target conditions two ballistic limits sometimes may be obtained: one at a velocity at which the fragments or projectiles remain intact upon impact and one at a significantly higher velocity where the fragments break up upon impact. The mechanism of penetration is different for each type of impact. However, for most missile-target combinations, consistent fragment break-up or consistent fragment integrity is maintained over the normally encountered velocity range.

Residual velocity measurements can be obtained for most of the tests that have been discussed by instrumenting the test set-up with added electronic measuring equipment. Accurate measurement of energy of specific target materials requires greater precision in velocity measurement than the usual V50 ballistic limit determination. Measurement of the energy absorption of a material from a penetrating missile can be readily calculated from the difference in kinetic energy of the missile before and after penetration. Three measurements are required for each round fired: the mass of the projectile; its striking velocity as it contacts the target; and its residual velocity as it just leaves the target. The projectile hardness and the presented area of the projectile's nose, obliquity, and hardness, chemistry, areal density, and homogeneity of the plate material should also be recorded. The shape of the projectile, the shape of the punched-out piece or pieces of metallic armor plate, and the velocity of this metal cause changes in the results. Very slight errors in

velocity measurement are greatly magnified in energy absorbing calculations if the velocity drop through the target is relatively small and the velocity levels are high[9].

The Ballistic Research Laboratories of Aberdeen Proving Ground have conducted extensive tests [10, 11, 12], on residual velocity investigations. The energy absorbing characteristics of materials when impacted by various missiles are useful in developing lethality and vulnerability data for use in the design of experimental armored vehicles. The behavior of most of the promising armor materials is similar. As the striking velocity is increased from a very low velocity to the ballistic limit of the material, theoretically no complete penetration (See Appendix A) occurs. When the striking velocities are in excess of the ballistic limit, the fragment will pass through the material with a residual velocity, the amount of which depends upon the excess of the striking velocity over the ballistic limit. Maximum energy is extracted by the material from the shell fragment when the striking velocity coincides with the ballistic limit. As the striking velocity becomes progressively higher than the ballistic limit, the residual velocity tends to approach the striking velocity. When the striking velocity of the missile is considerably in excess of the ballistic limit, damage to the plate generally becomes less severe and more localized, and less energy is absorbed during penetration.

The difficulty of measuring the velocity of a given fragment in the presence of a shower of other fragments of metallic armor thrown from the back of the plate also affects the test results on some residual velocity measurements. For nonmetallic armor there are virtually no secondary missiles thrown off the back of the armor, which makes the test less complex. In rigid plastic armor, (Doron II and bonded nylon) when striking velocities approach the ballistic limit the material is damaged by splitting and bending. Deformation of these plastic materials is greatest when there is no perforation since all of the missile's energy is absorbed by the material.

The measurement of transient and permanent deformation in a material is another ballistic concept that is employed in testing fragment-resistant armor materials. This information is useful to designers of helmets and helmet liners so as to enable the headpiece to have the required offset (distance between the head and the inside of the headpiece). A helmet[13] usually undergoes extensive transient and permanent deformation when impacted by the missile at velocities approaching the ballistic limit. The full force of the impact may well be transmitted to the head behind the helmet, and serious and extensive wounds may result even though the helmet has not been perforated. When deformation tests are conducted, a ballistic limit is first obtained on the end item and then velocities are selected, which are slightly less than the ballistic limit velocity, since maximum deformation and damage occurs at this velocity level. Elaborate instrumentation is required t obtain transient deformation ballistic data. An electronic instrumentation set-up for helmets and helmet liners is described in Reference Report 13.

## SUMMARY

The ballistic testing techniques which have been described have been developed by various research establishments with a view toward improving ballistic testing techniques, especially with regard to determining ballistic limits with minimum number of rounds and developing a simple and reproducible test. It can be concluded from the above discussion that much thought has been given to developing and standardizing a ballistic test for use in rating, comparing[14], and testing fragment-resistant armor. The ballistic test that is currently in use by the Ordnance Corps for specification acceptance of lightweight armor materials is the one employing fragment-simulating projectiles. It is considered to be the simplest, most reproducible, and most meaningful of any test developed to date.

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## APPENDIX A

All ballistic penetration tests may be termed as a resistance-to-penetration type of evaluations. The resistance of a material against penetrating forces of missiles which are classified as penetrators is measured. These penetrators may be of any regular or irregular shape and may be applied to materials at either slow or rapid rates of loading. An illustration of a commonly used static type of penetration (indentation) test with a spherical indenter is the Brinell test for hardness measurements. The Brinell hardness of a metallic material is nothing more than the resistance-to-penetration of that material by a spherical penetrator applied at slow rates of loading under definite conditions of test. The ballistic test for resistance-to-penetration is an illustration of rapid rates of loading with various shaped objects known as projectiles, missiles or fragments. The material under this condition is the armor. At the high rates of application of load, the resistance that the material offers is a result of a complex combination of factors (physical, mechanical and metallurgical) which are affected by high rates of strain. To date there is no one simple measure of the resistance-to-penetration of armor. Instead, there are in use several measures of the resistance-to-penetration of armor. Each of these is based more or less on practical considerations and is expressed as the striking velocity of a given projectile or fragment causing a preselected amount of damage. Therefore, the amount of preselected damage serves as the criterion for these different measures of penetration. Three such criteria, the Army, Protection and Navy Ballistic Limits, which are employed in rating armor materials are defined as follows:

Army Ballistic Limit - The critical or limit velocity at which the specified projectile will be borderline in penetrating the armor being impacted according to the "Army" criterion. (Although historically it was first employed in Army studies, it should only be considered at present as a term which defines a specific type of ballistic limit.) In this ballistic test a complete penetration occurs whenever a projectile or fragment has penetrated the armor sufficiently to permit at least a pinhole of light to pass through a hole or crack developed in the armor, or the front of the fragment or nose of the projectile can be seen from the rear of the armor. A partial penetration occurs when lesser damage to the armor occurs.

Protection Ballistic Limit - The critical or limit velocity at which the specified projectile will be borderline in penetrating the armor being impacted according to the "Protection" criterion. In this case a complete penetration occurs whenever a fragment or fragments from either the impacting projectile or the armor are caused to be thrown from the back of the armor with sufficient remaining energy to pierce a sheet of 0.020" thick 2024-T3 aluminum alloy placed parallel to and 6" behind the target. A fragment with this amount of energy is normally expected to produce lethal damage or its equivalent from a variety of mass-velocity combinations. Any fair impact which rebounds from the armor plate, remains embedded in the target, or passes through the target, but with insufficient energy to pierce the 0.020" thick aluminum alloy witness plate, is termed a partial penetration.

Navy Ballistic Limit - The critical or limit velocity at which the specified projectile will be borderline in penetrating the armor being impacted according to the "Navy" criterion. Although historically it was first employed in Naval activities, it should only be considered at present as a term which defines a specific type of ballistic limit. In these ballistic tests a complete penetration occurs whenever the entire projectile or essentially the entire projectile passes completely through the armor. All other penetrations are classified as partial. No witness plates are employed in these tests.

Employing the above criteria, in assessing partial and complete penetrations, a ballistic limit can be defined as a striking velocity (feet per second) of a kinetic energy fragment or projectile above which complete penetrations (as defined above) of the armor target will predominate and below which partial penetrations of the armor will generally predominate. This is generally expressed as a Army, Protection or Navy (V50) ballistic limit and is a critical velocity of a fragment or a projectile at which 50% complete penetrations and 50% partial penetrations of the armor target can be expected on a limited statistical test. A protection (V50) ballistic limit is now generally employed by the Ordnance and Quartermaster Corps in assessing the ballistic efficiency of armor materials.

The inherent variables within a material and the variables in any ballistic test such as slight difference in weights of projectiles, orientation of projectiles at time of impact, etc., introduce into the test a probable "zone of mixed results." As the name implies this zone of mixed results may contain one or more impacts which completely penetrate the material under test at velocities below those of other impacts which fail to effect complete penetration. This zone of mixed results can vary up to several hundred feet per second depending upon projectile reaction and the mechanism of penetration. However, in tests of lightweight armor against fragment simulating projectiles, the zone of mixed results is generally less than 100 feet per second.

A protection (V50) ballistic limit of fragment resistant materials is generally computed by averaging ten fair impact velocities comprising the five lowest velocities resulting in complete penetration and the five highest velocities resulting in partial penetration. A maximum spread of 125 feet per second is permitted between the lowest and highest velocities employed in the determination of the ballistic limit. In cases where the spread between the lowest complete and highest partial velocities is greater than 125 feet per second the ballistic limit shall be based upon 14 velocities, 7 of which result in the lowest complete penetrations and 7 which result in the highest partial penetrations. All velocities employed in the determination of the ballistic limit are corrected to striking velocities.